# DESIGN OF A MULTICHORD OPTICAL INTERFEROMETER WITH AN AXIAL FIBER-OPTIC PROBE TO MEASURE ELECTRON DENSITY IN A FIELD-REVERSED CONFIGURATION[*]

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*Abstract*

We present the design of a four-chord laser interferometer system operating at 633 nm that will measure the electron density of field-reversed configurations (FRCs) produced by the magnetized target fusion (MTF) experiment at the Air Force Research Laboratory. The design is a modified version of an eight-chord system previously used to provide time-resolved information about the spatial distribution of electron density in a similar FRC experiment. With the current system, a fanned array of laser beams will probe the plasma through the FRC midplane along four different chords, and the optical phase shift of each beam relative to a reference beam will be used to infer the line integrated electron density. In addition, a new feature of our design will be the option of diverting any or all of the four probe beams into single-mode optical fibers whose collimated outputs can be used to probe different axial locations simultaneously. This fiber-optic probe beam modification will enable us to place the interferometer system's optical table at a safe distance from the MTF-FRC experiment when destructive tests involving plasma compression by a solid metal liner imploded by the Shiva Star capacitor bank are attempted.

## I. INTRODUCTION

A research collaboration has been underway for several years between the Air Force Research Laboratory (AFRL) and the Los Alamos National Laboratory (LANL) to develop a field-reversed configuration (FRC) experiment whose goal is compressive heating of an FRC plasma to fusion-relevant densities and temperatures. Details of the efforts to produce an FRC with parameters suitable for subsequent adiabatic liner compression, along with those of vacuum liner implosion experiments that were performed at AFRL's Shiva Star facility to establish the feasibility of producing a suitable imploding liner, have been published in various references [1–3]. Current work is focused on integrating these two experiments in order to demonstrate Magnetized Target Fusion (MTF) in the laboratory. The integrated demonstration experiment, known as the Field-Reversed Configuration Heating Experiment (FRCHX), will be performed at AFRL's Shiva Star facility [4].

Measurements of the spatial distribution of electron density as a function of time are critical for determining the behavior of the FRC plasma, both during its initial azimuthally symmetric phase, and during the subsequent time when an $n = 2$ rotational instability takes hold. This mode saturates rapidly, at which point the plasma density rotates with a roughly fixed profile. In order to characterize the radial profile of the electron density with adequate time resolution before the compressive heating phase of the experiment takes place, a four-chord interferometer system operating at 633 nm (He-Ne laser wavelength) has been designed and is being assembled for use on FRCHX. This paper describes the details of that diagnostic.

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In Section II, we present the details of the optical design of the four-chord interferometer. Section III consists of a description of the demodulator circuit that serves to process the interferometer's optical signals in order to determine the relative phase shifts between the probe beams and the reference beam. A discussion of how Abel and tomographic inversions can be used to extract the electron density profiles from the optical phase shift data appears in Section IV. In Section V, we describe a new feature of our optical design, the use of a fiber-optic probe beam to enhance the functionality of this diagnostic, particularly when the actual MTF-FRC plasma injection/implosion experiments are performed. Finally, Section VI summarizes by conveying the current status of our interferometer system and what remains to be done before it can be implemented on the upcoming series of MTF-FRC experiments at AFRL.

## II. OPTICAL DESIGN

The design of our four-chord interferometer system is a modified version of an eight-chord system that has been successfully used in the past to obtain time-resolved data for the spatial distribution of electron density in the FRX-L experiment at LANL [5]. An illustration of the interferometer, whose optical components are mounted on a stainless steel rectangular optical table with a rectangular cutout to accommodate the quartz FRC formation tube, appears in Fig. 1.
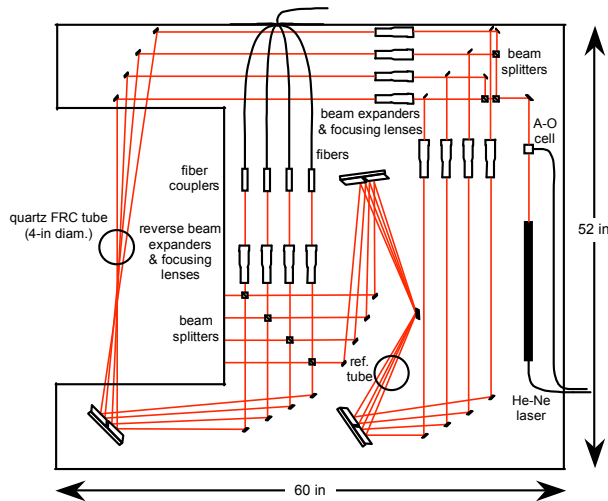


**Figure 1.** Scale drawing of the four-chord interferometer system showing its primary components. The optical table is oriented horizontally, and the quartz FRC formation tube is mounted vertically, passing through the rectangular cutout. The probe beams intersect the plasma through the FRC midplane.

The source of all the probe and reference beams is a single 22-mW linearly polarized He-Ne laser operating at a wavelength of 633 nm with a $TEM_{00}$ output mode. The output beam diameter is 0.7 mm. The apparatus is essentially a Mach-Zehnder interferometer, with the exception that it has multiple paths folded for compactness. Furthermore, rather than using the usual beam splitter to separate the initial beam into probe and reference branches, a flint glass acousto-optic Bragg cell, driven by an 80-MHz piezoelectric, splits off half the initial beam power by diffraction to supply the four reference beams. The optical frequency of the reference beams is thereby Doppler shifted by 80 MHz, which allows for the quadrature mixing needed to determine phase shift between the reference and probe beams unambiguously.

The components on the optical table are enclosed by a Lexan™ dust cover purged by filtered air impelled by a squirrel cage blower with an external motor isolated from the air stream in order to minimize air heating. The laser tube is contained within a small partitioned volume to isolate it from the rest of the optical table. To avoid the effects of radio frequency (RF) noise produced by the FRC experiment, the laser tube and its high voltage cable are enclosed in a copper braided tube clamped to a solid copper feedthrough tube entering a power-filtered RF-tight enclosure containing the laser power supply. The enclosure is powered externally by a battery powered uninterruptible power supply, which is unplugged from the AC power wall outlet during the shot. Nonconducting or, where not possible, nonmagnetic materials are used to minimize the Lorentz force interaction with the pulsed magnetic field produced by the experiment.

To create four probe and matching reference beams, an array of cubic beam splitters is used to split both beams into halves and then quarters. The angle of separation of the original probe and reference beams is sufficiently small (14.4 mrad) that this subsequent splitting is performed for both by the same cubic splitters. Thereafter, the reference beams are individually picked off by mirrors and sent to matched reference paths, as shown in Fig. 1.

The probe and reference beams for each channel are expanded by a factor of 6 to about a 1-cm diameter and then focused to a diffraction limited waist within the fused quartz FRC formation tube by lenses placed at the output of each beam expander. Focusing the beams in this manner mitigates the refractive distortion that arises from the substantial azimuthal ripples in the fused quartz tube wall. The plane of polarization for the laser is chosen to be normal to the tube's *z* axis to maximize the transmission coefficient of beams probing chords of high impact parameter (*i.e.*, minimum distance to the *z* axis). A similar, but truncated, fused quartz tube placed in the paths of the reference beams' matches the cylindrical lensing and slight refractive deflection of the beams due to passage through the tube wall. Chordal impact

parameters up to 95% of the tube's inner radius can thus be probed successfully, based on bench tests. The tube's inner and outer radii are 5.25 and 5.50 cm, respectively.

After traversing the FRC chamber, the probe beams pass through laser line filters to minimize plasma light transmission. They are then recombined with their respective reference beams by cubic beam splitters and fed into multimode optical fibers via reversed 6x beam expanders and converging lenses on the fiber mounts. The reference beams follow a nominally identical optical path, except for the absence of plasma, but they are folded up to save space. The recombined reference and probe beams gives rise to four channels of intensity modulated light with a base line frequency of 80 MHz that result from the difference in their optical frequencies. The time dependent electromagnetic phase shift of each probe beam relative to its reference beam equals the phase shift of this beat wave from its 80 MHz base line.

## III. DEMODULATOR CIRCUIT

Once the four recombined beams from the interferometer are collected and focused onto the output optical fibers, they are transported by those fibers to a remote RF-shielded enclosure. There, the intensity modulated light is converted to phase modulated 80 MHz RF signals by optical receivers. The RF signals are mixed by in-phase quadrature IQ demodulators with 80 MHz local oscillator (LO) signals split off from the Bragg cell driver. One of the two IQ demodulator output signals for each channel probe corresponds to $\sin\phi$, while the other corresponds to $\cos\phi$, where $\phi$ is the phase shift between the RF and LO inputs. This phase shift is, in our geometry, equal to that of the corresponding probe beam relative to its reference beam. Subsequent 60-MHz low-pass filters remove high frequency leakage and upper band interference from the demodulator outputs and define the instrument's diagnostic bandwidth.

The eight output signals from the demodulator circuit (two for each of the four diagnostic channels) are recorded by transient digitizers (located in the same RF-shielded enclosure) and then numerically converted to phase shift $\phi$ versus time $t$ from the multivalued arctangent of the ratio. Additional details of how the signals are processed to obtain $\phi(t)$ unambiguously for each interferometer chord are given in Ref. [5]. The component layout for the four-channel demodulator circuit that processes our interferometer signals is illustrated in Fig. 2.
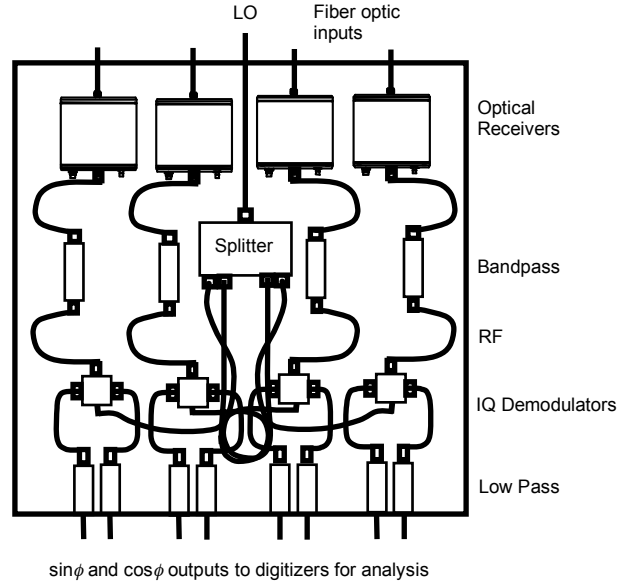


sin$\phi$ and cos$\phi$ outputs to digitizers for analysis

**Figure 2.** Layout of the demodulator circuit that processes the fiber-optic output signals from the interferometer.

## IV. INVERSION TECHNIQUES

With the $\phi(t)$ data for each diagnostic channel, we shall infer the radial electron density profile $n_e(R, t)$ in the FRC by performing inversion routines with suitable corrections to $\phi$ arising from factors such as the acoustic vibrations induced by the pulsed magnetic bias field and the bulk heating of the fused quartz vacuum vessel [5]. Analytically, the phase shift $\phi$ of a given probe beam relative to its reference is given by

$$A\phi(t) = \int_L n_e \, dl = \int_w^{R_0^2} \frac{n_e(s, t)}{\sqrt{s - w}} \, ds, \qquad (1)$$

where the path integral of the electron density is along the length of the chord defined by a given probe beam [6]. Here, $A = 5.62 \times 10^{16}$ cm$^2$/rad for the He-Ne laser wavelength of 633 nm, $w = p^2$, where $p$ is the impact parameter of a given chord (*i.e.*, the distance of closest approach to the $z$ axis of the cylindrical coordinate system defined by the longitudinal axis of the quartz FRC vacuum vessel), $R_0$ is the radius of the quartz vacuum vessel tube, and $s = R^2$, where $R$ is the radial coordinate in the cylindrical coordinate system of the FRC. The boundary condition is $n_e(R_0, t) = 0$.

Our measurements will consist of $\phi(w, t)$ for $q$ discrete chords with impact parameters $p_k$ (where $k = 0, 1, ..., q-1$, and $p_k + 1 > p_k$), so that $w_k = p_k^2$, and $\phi_k = \phi(w_k, t)$. For our four-chord interferometer system, $q = 4$.

Initially, the FRC exhibits approximate azimuthal symmetry. Our plan for calculating the radial density profile is to exploit this feature by using Abel inversion algorithms to obtain $n_e(s, t)$ at radii equal to the impact parameters for each of the 4 chords: $n_k = n_e(w_k, t)$, where $k = 0, 1, 2, 3$. Two complementary inversion routines can be used. One produces a result with a discontinuous gradient, but previous experience shows that is fully consistent with the phase-shift data in the sense that line integration along the probed chords reproduces the original phase-shift data precisely [7]. It is adequate for inferring spatially integrated properties such as mass and moment of inertia per axial unit length.

The other Abel inversion routine that we may employ produces a continuous function and gradient, with explicit weight given to reducing the characteristic magnitude of $\partial^2 n_e / \partial R^2$ to increase smoothness at the expense of spatial resolution. This approach is more suitable for quantifying peaks in the density profile and gradients needed for magnetohydrodynamic (MHD) equilibrium analysis, from which basic FRC properties such as plasma temperature and poloidal flux can be inferred [7].

After a time, the Abel inversion routines are no longer useful due to the fact that an FRC spontaneously gains angular momentum until the parameter $\Omega_R/\Omega_{Di}$ reaches a critical value of order unity. (Here, $\Omega_R$ and $\Omega_{Di}$ are the FRC's rotational and ion diamagnetic drift frequencies, respectively.) At this point, a rotational instability with azimuthal mode number $n = 2$ develops, and it eventually saturates. One can calculate the two-dimensional $n_e$ distribution in the midplane of this saturated state, since line-integrated measurements of $n_e$ versus time taken along several chords of a rigidly rotating subject constitute a sufficient data set for a tomographic inversion routine to be used.

Once the electron density profiles are obtained for the saturated state, integrated properties such as mass and angular momentum per unit length in the axial direction can be obtained for correlation with the corresponding properties of the earlier azimuthally symmetric phase. Additional details of the inversion techniques mentioned here and how they can be applied to data that will be obtained with our interferometer are discussed in Ref. [7].

## V. FIBER-OPTIC PROBE BEAM

In order to enhance the functionality of our plasma density diagnostic, the interferometer system will incorporate a novel feature that will distinguish it from the one used previously on the FRX-L experiment [5]. The original four-chord geometry described above will be modified by diverting one of the four probe beams into a single-mode optical fiber. An illustration of the interferometer system, modified to make use of a fiber-optic probe beam, is given in Fig. 3.
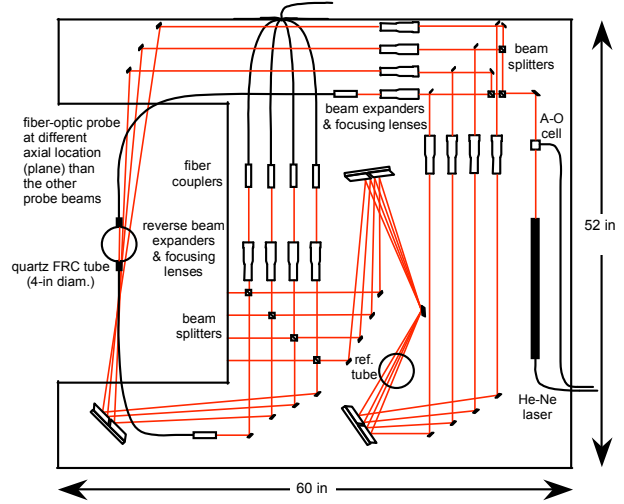


**Figure 3.** Scale drawing of the modified four-chord interferometer system. Here, one of the four chords consists of a fiber-optic probe beam that can be moved axially along the length of the FRC formation tube.

An interferometer system for pulsed power applications using a fiber-optic probe beam has been successfully demonstrated [8], and we shall adapt this technique to our configuration by placing a single-mode optical fiber on the vacuum vessel to launch a probe beam at an axial location other than the one occupied by the three other probe beams. A corresponding single-mode optical fiber will be placed directly opposite the launching fiber to collect phase-shifted light. In this way, the electron density profile will be obtained for different values of $z$ simultaneously during an FRC discharge.

For the sake of the present discussion, we have assumed that only one of the four probe beams has been diverted to a single-mode fiber. In principle, some or all of the beams can be transported by single-mode fibers and used as described above to obtain data for $n_e$ at up to four different axial locations.

Our diagnostic will thus have its versatility increased by making it possible to operate in two different modes. The configuration described in Sec. II makes it possible to measure electron density at a single value of $z$ along four different chords, which is the optimal configuration for obtaining the best spatial resolution of the radial profile. By making the modification described in this section, however, it will be possible to measure $n_e$ at one or more different values of $z$. The trade-off here is that this approach will require sacrificing some radial resolution for the sake of being able to monitor the density at different axial locations during the translation of the FRC along the $z$ axis that will take place when the plasma is injected into an imploding metallic liner for our upcoming compressive heating experiments [4].

Another aspect that makes the fiber-optic probe beam technique particularly useful for the MTF-FRC plasma

injection/implosion experiment is the fact that we can probe the plasma remotely. By simply extending our single-mode probe to some suitable length, it will be possible to locate and operate the interferometer's optical table at a safe distance away from the destructive test involving injection of the FRC into an imploding solid liner. This will ensure the survivability of the more expensive optical elements and electronics and require that we sacrifice only the ends of the optical fibers that are used to transport the probe beam(s) and collect the phase-shifted light.

## VI. SUMMARY

Assembly of the four-chord interferometer system for AFRL's MTF-FRC experiment is underway. Following the design described in Sec. II and shown in Fig. 1, optics are being installed and aligned on our optical table. Once those tasks are completed, the optical system and its accompanying demodulator electronics (discussed in Sec. III and shown in Fig. 2) will be tested. The diagnostic will then be fielded on the "static" FRC experiment in order to characterize its operation and obtain radial density profiles at a fixed axial location.

Once radial profiles of the electron density have been satisfactorily obtained in this configuration using the inversion techniques mentioned in Sec. IV, we shall modify our system to incorporate the use of at least one fiber-optic probe beam, as shown in Fig. 3. Following the approach detailed in Sec. V, measurements will be taken of the electron density at one or more axial locations. Finally, in conjunction with the plasma injection/imploding liner experiment, the diagnostic will then be fielded using the fiber-optic probe remotely to protect the rest of the interferometer system from these destructive tests.

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